BOSTON UNIVERSITY

GRADUATE SCHOOL

Thesis

A Study of the "Grid" Structure in Certain Strong Spectrum Lines.

Submitted by

Lucien Bradford Taylor

(S. B., Boston University, 1918)

In partial fulfilment of requirements for the degree of Master of Arts.

1920

A Study of the "Grid" Structure

in Certain Strong Spectrum Lines.

Synopsis.

The purpose of this investigation has been to explain the peculiar structure occurring in certain spectrum lines as given by the echelon grating, and called by Nutting the "grid", the work being concentrated upon Li λ 6104 in which the structure is especially prominent. After a brief historical survey to give the necessary setting, the apparatus employed is described, the construction of the special vacuum tubes being noted in detail.

The following results are then given:

Li λ 6104 has been observed in the vacuum tube (1) as a spectroscopic doublet in a very nearly simple condition, and (2) with the prominent grid structure. With the line as in (1), measurement of the difference in wave-length between the components was attempted but certain attendant difficulties rendered the determinations of little value.

The theory of secondary maxima was considered and a series of tests applied, the results of which made it possible to explain the grid upon this basis. From the width of the line (obtained by measurement) and from theoretical considerations it was concluded that only such lines as have considerable breadth can show this structure, and further that when a line attains a width equal to one-fifth the distance between the orders it becomes unsuited for study with the echelon.

Historical Survey.

All spectrum lines are sensitive to changing conditions in the source. Such changes may vary the intensity, width, structure, or even wave-length of the line. Increase in the intensity of the source brightens, and in many cases broadens, the line, the change in width being more apparent in lines which are originally diffuse in character. The lines in arc and spark spectra are generally broader and more intense than those given by vacuum tubes, those in the last case being often weaker and always narrower on account of the low pressure and the small amount of vapor present in the source.

In 1896 Humphreys and Mohler[1] discovered that an increase in pressure causes an actual shift of the position of spectrum lines toward the red. The change in wave-length for a given line is directly proportional to the increase in pressure.

Exner and Haschek[2] in 1901 stated that the spark lines of titanium show a considerable shift as compared with the arc lines of the same substance.

Kent[3] made a careful investigation of the spectra of titanium and zinc with a concave grating, and found a variability in both arc and spark spectra.

The work of St. John and Babcock[4] on the "Pole Effect" has shown that the variations in arc spectra are so great that special attention must be given, not only to the amount of current used, but also to the portion of the arc taken as a source.

In the case of spark spectra the shift is produced by changes in the conditions of the electric circuit, i.e.,

in capacity, inductance, ohmic resistance, and auxiliary spark gap. This fact becomes of great importance in stellar work, especially in radial velocity determinations, where a spark spectrum is used for comparison. Furthermore, it is clear that any measurements of the wave-lengths of spark spectrum lines are of little value if the circuit conditions are not fully stated.

Considerable interest has been aroused in finding an explanation of these shifts. In 1906 Nutting[5], after an intensive investigation of line structure with a 30 plate echelon, stated that certain lines in the arc spectra of zinc, cadmium, lithium, and several other elements are not single as previously supposed, but possess satellites. He found certain Zn and Cd lines double or triple, and Li λ 6104 having two to five components on a continuous ground, depending upon the intensity of the source.

Janicki[6] took objection to Nutting's results and attributed them to "ghosts" in the echelon. He, using a Lummer plate which he claimed to be superior to Nutting's instrument, had always found these same lines single, as had Michelson, Fabry and Perot, Hamy, Gehrcke and van Baeyer. In the same paper he seeks to explain the shift that Kent had found as due to unsymmetrical reversal which would not be resolved in gratings of low resolving power, but would appear as a shift in the centre of intensity of the line.

Kent, however, in later work[7] with a 20 plate echelon confirmed Nutting's results in the case of the three blue Zn lines, and in addition observed an enhancement of the red

satellites, when the condition of the source was such as to produce a shift under low resolving power. He accordingly advanced the theory that the apparent shift can be accounted for by the relative brightening of the red components. He found, further, that sometimes the satellites endured and even grew brighter as the main line became fainter. Also in the case of some lines the structure appeared in the spark when it did not in the arc. The occurrence of these lines cannot, therefore, be explained on ordinary "ghost" or false line theory as Kent was using an echelon that gave no false lines. His work, then, seemed to point to the conclusion, that the structure which Nutting observed was real, that is, indicative of actual radiations of these specific wave-lengths in the source.

The work of Michelson, Janicki and others, referred to above, has shown the Zn lines $\lambda\lambda$4680 and 4722 to be single and λ4810 to have one satellite. Paschen and Kent[8] have found Li $\lambda\lambda$6104 and 6708, as given by a vacuum tube, spectroscopic doublets, and have measured the difference in wave-length between the components. King[9] in work on electric furnace spectra has confirmed their results for λ6708. Although using an echelon of 33 plates they observed no other structure in the lines. Nutting's instrument, however, had about 50% greater resolving power than theirs.

In all the lines which exhibit it, this structure, under the best conditions, consists of from four to eight, or more (if parts of adjacent orders be included) equally brilliant and equidistant components, generally on a continuous background. Accordingly, from its characteristic

appearance Nutting has called it the "grid". The cause of this structure has presented so interesting a problem that Kent has devoted considerable time to it. The following is a summary of his results—obtained with the assistance of Mr. H. E. H. Greenleaf and later of Dr. Lucy Wilson and the writer—which lead directly to the work undertaken in this paper under Kent's guidance.

(1) Using a carbon arc and sometimes a Pfund arc, in moderate vacuo, the "grid" was found particularly well marked in Zn $\lambda\lambda$4680, 4722, and 4810. In λ4810 it was especially brilliant and well suited for study. Most of the work was then done upon this line. At low values of current and pressure the line was found in various conditions: single, double, triple, or quadruple, the structure probably depending upon the amount of vapor present and upon whether the echelon was in single-, or double- order condition. The outer components exhibited a rapid "in and out" motion. Under the same conditions the line always appeared single when viewed in the third order of the plane grating. The grid which was usually seen at atmospheric pressure, was clear at low pressure if a large amount of vapor were present. The line, however, was sometimes double at atmospheric pressure, in which case the grid could be brought out by an increase in the current. At the edge of the arc the grid was less clearly marked than at the centre, as might be expected since the vapor must be less dense at that point.

(2) Some work was done upon Li λ6104 with the carbon arc in air. The grid was very brilliant at low current (3 to 4 amperes), but unlike the Zn lines, a broad

structureless line extending over more than the distance between two orders was observed if too much vapor were present, as when the arc was first started. It was noted that, under the latter conditions, the grid did exist at the edge of the arc and then developed in the centre as the vapor diminished. When the echelon gave the grid, the grating showed a broad line strongly reversed.

(3) As a test of the true nature of the structure, the 12 inch Lummer plate from the Bureau of Standards, a very fine instrument, was crossed with the echelon, i.e., they were so placed that the dispersion of one was in a direction normal to that of the other. With this arrangement Li λ6104 gave at 10 amperes an <u>oblique</u> point system, which showed that the grid consists of lines of different wave-lengths, for if the lines were separate maxima of the same wave-length the points would lie on lines coincident with those given by the Lummer plate alone.

(4) The Mercury lines were investigated using a specially designed arc lamp constructed of quartz to allow of high temperatures. The most important results were obtained with Hg λ5461. This line is notably complex, in fact Nagaoka has claimed to have found 19 satellites in it with a 35 plate echelon. With the arc "end on" a grid of four components was obtained in the main line. When viewed "side on" only the usual complex structure appeared with no reversal of the main line. This was with a current of from 2 to 5 amperes. At the same time with the tube set "end on", the grating showed the entire line to consist of four broad components. This seemed to confirm the structure as given by the eche-

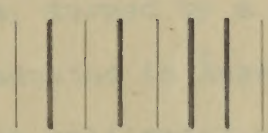
structureless line extending over more than the distance between two orders was observed if too much vapor were present, as when the arc was first started. It was noted that, under the latter conditions, the grid did exist at the edge of the arc and then developed in the centre as the vapor diminished. When the echelon gave the grid, the grating showed a broad line strongly reversed.

(3) As a test of the true nature of the structure, the 12 inch Lummer plate from the Bureau of Standards, a very fine instrument, was crossed with the echelon, i.e., they were so placed that the dispersion of one was in a direction normal to that of the other. With this arrangement λ6104 gave at 10 amperes an <u>oblique</u> point system, which showed that the grid consists of lines of different wave-lengths, for if the lines were separate maxima of the same wave-length the points would lie on lines coincident with those given by the Lummer plate alone.

(4) The Mercury lines were investigated using a specially designed arc lamp constructed of quartz to allow of high temperatures. The most important results were obtained with Hg λ5461. This line is notably complex, in fact Nagaoka has claimed to have found 19 satellites in it with a 35 plate echelon. With the arc "end on" a grid of four components was obtained in the main line. When viewed "side on" only the usual complex structure appeared with no reversal of the main line. This was with a current of from 2 to 5 amperes. At the same time with the tube set "end on", the grating showed the entire line to consist of four broad components. This seemed to confirm the structure as given by the eche-

lon. This effect in the grating, however, can be explained by the broadening and fusing of satellites near to the main line.

(5) Further work on lithium with a carbon arc in vacuo brought the following results. In λ6104 the grid disappeared at high current (20 amperes), leaving a broad structureless line. Diminishing the pressure and the current brought out the grid very clearly, and at very low values of pressure and current certain components grew faint leaving the structure appearing thus:



In λ6708 no grid was seen in the arc. The line was broad and structureless at atmospheric pressure; but at low pressure and small current the two components of this spectroscopic doublet were visible.

The perduring of certain lines in λ6104 made it seem probable that the grid was built upon some simple structure as a basis — possibly the two components of the spectroscopic doublet itself. It was accordingly decided to use a vacuum tube of the type employed by Paschen and Kent, in which the line could be obtained as a simple doublet, and to endeavor to build up the grid from the two lines, observing the changes in conditions necessary to produce this result. Having this in view the work was continued by the writer with the apparatus now to be described.

Apparatus.

A. Optical Systems.

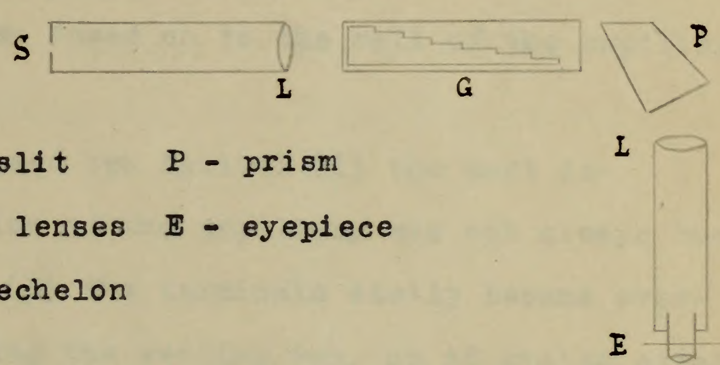
(1) Echelon gratings. Two echelons were employed: one, made by Petitdidier, consisting of 30 plates each 23.29 mm. in thickness, 1.00 mm. step, and aperture 31.0 by 35.5 mm.; and the other, made by Porter having 30 plates of thickness 14.76 mm., step 1.00 mm., and aperture 31.0 by 33.0mm. Most of the work was done with the Petitdidier instrument, it being the larger and better of the two.

The lines were separated by means of an Hilger constant deviation prism, turned by a micrometer screw, the drum of which was graduated in Ångstrom units.

The lenses of the collimator and the telescope were achromats of about 50 cm. focal length and 5 cm. aperture.

The telescope was fitted with a micrometer eyepiece having an ocular of 25 diameters magnification.

The method of mounting is shown in the sketch.



S - slit P - prism
LL - lenses E - eyepiece
G - echelon

An achromatic doublet of 7 cm. aperture and 30 cm. focal length projected an image of the source upon the slit.

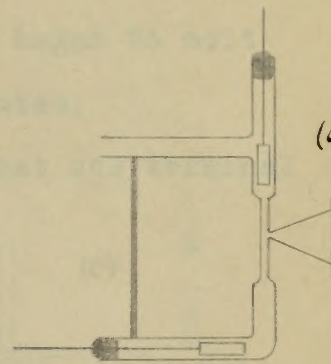
(2) Plane grating. An Anderson plane grating was also used having an aperture of 3½ by 5 inches, and ruled with 15,000 lines per inch. It was set in a Littrow Mount with a lens of 30 feet focal length. An image of the source was projected upon a bi-lateral slit by means of a single

achromatic lens of 4 cm. aperture and 30 cm. focal length. The third order on the right side of the normal was employed, the lines being viewed through a Hastings triplet as ocular.

B. Sources of Light.

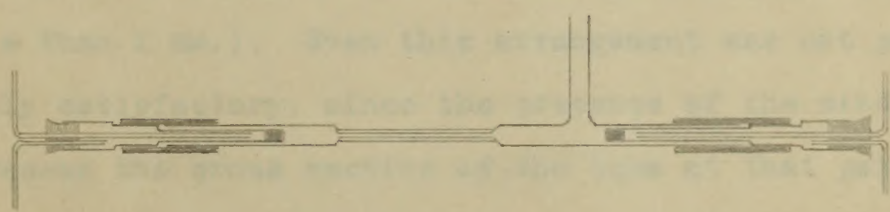
(1) Vacuum tube. In an effort to secure a satisfactory vacuum tube several types were designed. The glass blowing was done by F. S. Macalaster of the Jefferson Physical Laboratory of Harvard University. Tubes of the following patterns were tried:

(a) A tube made of quartz glass, with a window of ordinary glass. The electrodes were of heavy brass wire threaded into cylindrical aluminium tips, and were sealed into the tube with sealing wax. The salt was dropped in through the window, the tube being held horizontally, and then fused on to the wall of the capillary with a Bunsen flame.



(a)

This tube possessed two faults: (1) the most intensely excited portion of the capillary was not always behind the window; and (2) the terminals easily became overheated, thereby melting the sealing wax, or if cooled externally with wet cotton the glass was cracked by the expansion of the electrodes.



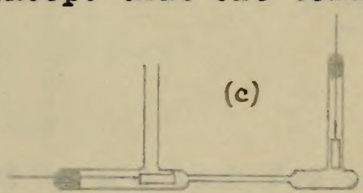
(b)

(b) The first tube of this type was of Pyrex glass but

the excessive heat melted it, so that quartz was resorted to. Hollow terminals of brass with aluminium caps were used, which could be cooled internally with running water. They were sealed into the tube with heavy rubber compression tubing, the surface of the glass and of the terminals having first been covered with Ramsay's lubricant.

This tube worked fairly well. Any desired portion of the capillary could be used as a source. The glass around the terminals became so hot, however, in spite of the wet cotton which covered it, that it began to melt the rubber after a run of a very few minutes.

(c) This one was similar to (b) except that one terminal was put in perpendicular to the capillary and a window was blown in the end so that

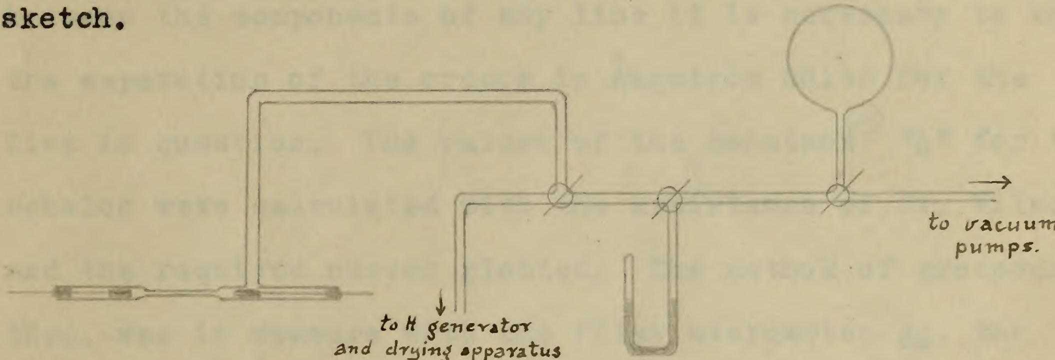


the tube could be used "end on". It proved to be the most satisfactory type, especially when fitted with electrodes of light brass wire having solid brass caps 6 mm. in diameter. These terminals were sealed in with DeKhotinsky cement and each joint cooled with a water jacket.

In the last part of the work this tube was used with a window in the side, as in (a), the opening into the capillary being no larger than the capillary itself (less than 1 mm.). Even this arrangement was not perfectly satisfactory, since the presence of the window increased the cross section of the tube at that point and thereby reduced the brilliancy, and, furthermore, the opening easily became clogged.

Each of these tubes when in use was supported on a

suitable stand, and connection was made by means of glass tubing from the inlet shown in the diagrams to a Gaede mechanical rotary vacuum pump in series with a Gaede mercury pump. The system also contained a manometer, a large bulb to steady the pressure and to facilitate its regulation, and a Kipp hydrogen generator with a drying apparatus of calcium chloride and sulphuric acid. The general arrangement is shown in elevation in the sketch.



The tube was at first excited by a 3 inch Cox induction coil with a mercury, or an electrolytic break; but the heavy current demanded proved too great an overload, so it was abandoned. In its place was used a Holzer-Cabot Motor-Generator set, 4.5 K.W., 110 volts, giving 60 cycles per second and feeding a 5 K.W. oil transformer (ratio of transformation 110 to 30,000). An adjustable rheostat controlled the primary current which varied from 10 to 40 amperes. (A 1 K.W. air-cooled transformer was tried, but it proved inadequate.)

There were occasionally used a condenser of 0.0226 microfarad in parallel with the vacuum tube, an inductance (described in a previous paper by Prof. Kent[7]) and a horizontal variable spark gap in series.

(2) <u>Arc.</u> The arc in air used was formed between two cored carbons in the 110 volt circuit, and ionized with

a solution of the salt or with metallic zinc. Adjustable rheostats controlled the current, which varied from 1 to 10 amperes.

Method of Measuring Differences of Wave-Length by Means of the Echelon.

In order to determine the difference in wave-length between the components of any line it is necessary to know the separation of the orders in Ångström units for the line in question. The values of the constant (10) "b" for the echelon were calculated with the assistance of Dr. Wilson and the required curves plotted. The method of procedure then, was to measure with the filar micrometer dn, the distance in scale divisions between the two components under consideration, and dn', that between the same components in adjacent orders. The value of the wave length difference is $\Delta\lambda = \frac{dn}{dn'}\Delta\lambda_0$, where $\Delta\lambda_0$ is the separation of the orders in Ångström units as taken from the curve. The prism scale was determined from lines of known wave-length as given by an Argon tube, and the ratio of the prism dispersion to that of the echelon (varying from .4% to 1.2%) obtained. Then, since the prism and the echelon as mounted disperse in the same direction, this could be applied as a *negative* correction to $\Delta\lambda$ if the accuracy of the measurements warranted it.

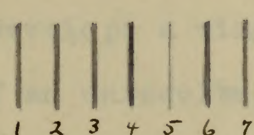
Results of the Investigation.

The problem at hand was to explain the grid structure, efforts being centred upon Li λ6104, since the structure was especially persistent and brilliant in that line.

Many runs were made with the various lithium tubes under different conditions of pressure and excitation. Changes in the electric circuit conditions had but little effect upon the character of the line save in brilliancy, the best results being obtained with 40 amperes primary current and no capacity, inductance, nor auxiliary spark gap. The line proved most sensitive, however, to variations of pressure, as had been expected.

The general method of procedure was to start the discharge at 5 to 6 cm. pressure and gradually exhaust further. Greater clearness was obtained if the tube were occasionally flushed with hydrogen. The results obtained can be summarized as follows:

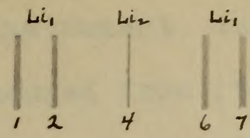
In Li λ6104 the grid is present at a pressure of 4 to 5 cm. Upon reducing the pressure the intensity of all lines diminishes but certain ones fade more rapidly giving the same structure as last noted in the vacuum arc, viz:

Red ⟵  ⟶ Violet

Measurements made upon all seven of these lines agree with those made upon the same lines in the arc, and show the $\Delta\lambda_g$, or the difference in wave-length between any two grid components, equal to 0.052 Å.

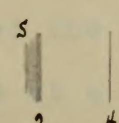
Upon further exhaustion component 5 disappears and

then 3, leaving the structure thus:

Red ⟵ 

⟶ Violet

4 being fainter is clearly the weaker component (Li_2) of the spectroscopic doublet. 1 and 2 together, then, seem to make up the stronger component (Li_1), 6 and 7 being the same lines in the next order, that is, Li_1 is in double-order-condition. This line has not been seen absolutely single, but at the highest vacuum reached, the lines becoming too faint to observe well, 1 and 6 seem to disappear first, leaving 2, 4 and 7 as the perduring lines. It thus appears a question whether 2 is the true position of Li_1, or whether 1 and 2 together form the line in a self-reversed condition. It was known from the work of Paschen and Kent that Li_1 lies to the red side of Li_2. Therefore the difference in wave-length between the two may be the distance from 4 to 2, or from 4 to a point midway 2 and 1. Measurements of these two distances show the first to be about 0.104 Å, and the second about 0.131 Å. The value obtained by Paschen and Kent was 0.114 Å. It has been observed, however, that when the echelon is rotated so as to bring Li_1 into single-order-condition, i.e., into the centre or brightest portion of the field, 2 develops a wing as one disappears, giving the appearance of an unresolved satellite, s, thus:



In this condition the lines are much too faint for measurement, but the breadth of 2 seems to be about $\frac{1}{2}\ \Delta\lambda g$. If this is the true structure of Li_1 then Paschen and Kent

whose echelon had less than one-half the resolving power of the Petitdidier instrument, must have seen it as merely a broad line and measured from its centre of intensity. Interpolation between the values obtained by the writer as recorded above would give a result in fair agreement with theirs.

In order to confirm these conclusions it will be necessary to re-examine the line under better conditions of brilliancy and vacuum. If the satellite, s, truly exists and can be obtained narrow enough and sufficiently bright to be seen, the Petitdidier instrument with its great resolving power of 750,000 for this wave-length may possibly separate it clearly from the main component. Theoretically, as the doublets in the homologous series in Rb and Cs show a third line, similar components should exist in K, Na, and Li, the separation being increasingly less, and therefore the line and its component increasingly more difficult to resolve. At any rate until the stronger component of λ 6104 is obtained free from structure of whatever nature, the difference in wave-length between the two main components of this doublet must remain in doubt.

Having the lines in a simple condition, it is to be noticed that the grid is produced by the appearance of components to the red of Li_1 and Li_2 as the pressure is raised. It was at first thought that these might be caused by the twinning of the two lines together with the coming up of a satellite at a distance 2 $\Delta\lambda_g$ at the red of Li_1. On turning, however, to the Porter echelon, in which the angular separation of the orders is the same, but the dispersion only 0.7 that of the Petitdidier instrument, the grid was found to have the same spacing, in

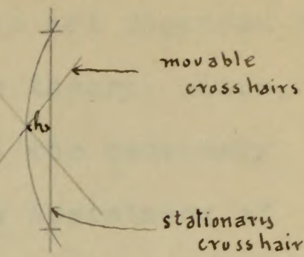
scale divisions, while the doublet components were of course nearer together. This, together with the fact that the grid presents the same appearance in all lines in which it occurs, $\Delta\lambda_g$ decreasing slightly with the wave-length, led to the suspicion that the structure is not characteristic of the source but finds its origin in the instrument.

Stansfield[11] has shown that the echelon can give secondary maxima which are produced by interference between rays which have undergone successive reflections within the plates. These maxima under proper conditions may become visible superposed upon the primary maxima. Stansfield has seen structure in Hg λ 5461 in a quartz arc at high current, which he suggested might be due to a secondary action, and which from his description is without doubt the same as that seen by Kent, Dr. Wilson and the writer when working upon this line. (See page 6).

The possibility of ascribing the grid to secondary maxima had been considered before, but it was not then thought that the structure met any of the requirements. The satellites were not narrower than what was then considered the primary line, their curvature was the same as this line and they moved across the field at the same rate. Now, however, the tests were reapplied in a different manner, regarding every line of the entire grid structure as a secondary maxima phenomenon, and quite conclusive results were obtained:-

(1) The curvature of one of the Hg yellow lines was compared with that of a grid line in Li λ 6104. By stopping down the echelon spectroscope slit a definite length of line was observed, and by setting the stationary cross-

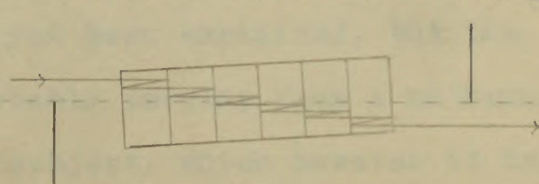
hair of the filar micrometer upon the ends of the line and the movable one upon its centre, the horizontal distance, h, from the ends of each line to its centre was measured. (See sketch) It was found that the curvature of the grid line was 20% greater than that of the primary spectrum line.



(2) By means of a small mirror in front of the slit the argon and lithium spectra were observed at the same time. The relative motion of the grid lines in Li λ6104 and a nearby Ar line was then studied as the echelon was rotated. During the change from one double-order-condition to the next double-order-condition in the Ar line, the grid lines in Li λ6104 moved across the field at a greater rate. Further, as the primary orders of Li λ6104 changed, the grid lines moved across the diffuse image of the primary action line in the same direction and at about twice the rate at which the primary was moving.

(3) Some of the steps of the larger plates of the Porter echelon were covered with a screen. As this was done the grid lines moved across the field a short distance(equal to about $\frac{1}{2}\,\Delta\lambda_g$).

(4) The light through the spectroscope was entirely cut off by means of horizontal screens covering one-half the aperture of the echelon at each end as in the figure. The echelon was then tilted by raising the end nearer the prism,



but no light came through by reflection within the plates

as predicted by Stansfield. This was the only negative result obtained in these tests, but it is not regarded by the writer as a serious objection to the theory, since, as will be shown, it is his opinion that the secondary maxima cannot become visible without the assistance of the light of the primary.

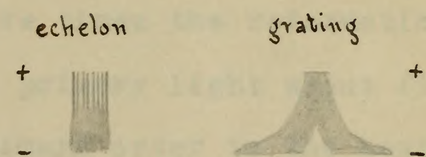
The results show quite conclusively that the grid structure is to be attributed to this secondary action. That the structure should be the same in both Porter and Petitdidier echelons is not to be wondered at, from the following consideration. The retardation producing the primary maxima is proportional to μ-1, while that of the light undergoing secondary action is proportional to 3μ-1. Therefore the relative retardation of the two actions in the same echelon is equal to $\frac{3\mu-1}{\mu-1}$, that is, it is a function only of μ. Consequently, since all echelons are made of substantially the same kind of glass, any two having equal separation of primary orders will have the same separation of secondary maxima. Moreover, since the value of $\frac{3\mu-1}{\mu-1}$ is approximately 6.5 for λ 6104, there should be 6.5 secondary maxima for every primary maximum. Stansfield's value for $\Delta\lambda_g$ is 0.041 Å. Our value of $\Delta\lambda_0$ for this wavelength is 0.262 Å. $\frac{0.262}{0.041}$ = 6.4 which is in close agreement with 6.5. In passing from one primary line to the same one in the next order, five grid components are counted. This discrepancy has not yet been explained, but the reason therefor would probably develop from a mathematical consideration of the subject, which however is beyond the scope of the present paper.

as predicted by Stansfield. This was the only negative result obtained in these tests, but it is not regarded by the writer as a serious objection to the theory, since, maxima will be shown, it is his opinion that the secondary maxima cannot become visible without the assistance of the light of the primary.

The results show quite conclusively that the grid structure is to be attributed to this secondary action. That the structure should be the same in both Porter and Petitdidier echelons is not to be wondered at, from the following consideration. The retardation producing the primary maxima is proportional to μ-1, while that of the light undergoing secondary action is proportional to 3μ-1. Therefore the relative retardation of the two actions in the same echelon is equal to $\frac{3\mu-1}{\mu-1}$; that is, it is a function only of μ. Consequently, since all echelons are made of substantially the same kind of glass, any two having equal separation of primary orders will have the same separation of secondary maxima. Moreover, since the value of $\frac{3\mu-1}{\mu-1}$ is approximately 6.5 for λ 5104, there should be 6.5 secondary maxima for every primary maximum. Stansfield's value for $\Delta\lambda$ is 0.041 Å. Our value of $\Delta\lambda$ for this wave-length is 0.262 Å. $\frac{0.262}{0.041}$=6.4 which is in close agreement with 6.5. In passing from one primary line to the same one in the next order, five grid components are counted. This discrepancy has not yet been explained, but the reason therefor would probably develop from a mathematical consideration of the subject, which however is beyond the scope of the present paper.

Stansfield stated, without explanation, that a short continuous spectrum, such as that presented by a broad line, might be favorable for the production of secondary maxima. This suggested an investigation of the width of Li λ 6104. It was accordingly studied in the third order of the plane grating using the open arc.

The grid is always seen more clearly in the echelon at the positive pole of the arc, and is usually well marked at the positive pole when the line is broad and structureless at the negative pole. Under this latter condition the line was seen in the grating broad and strongly reversed at the negative pole, and relatively narrow and structureless at the positive pole, that is, at the same pole which was giving the

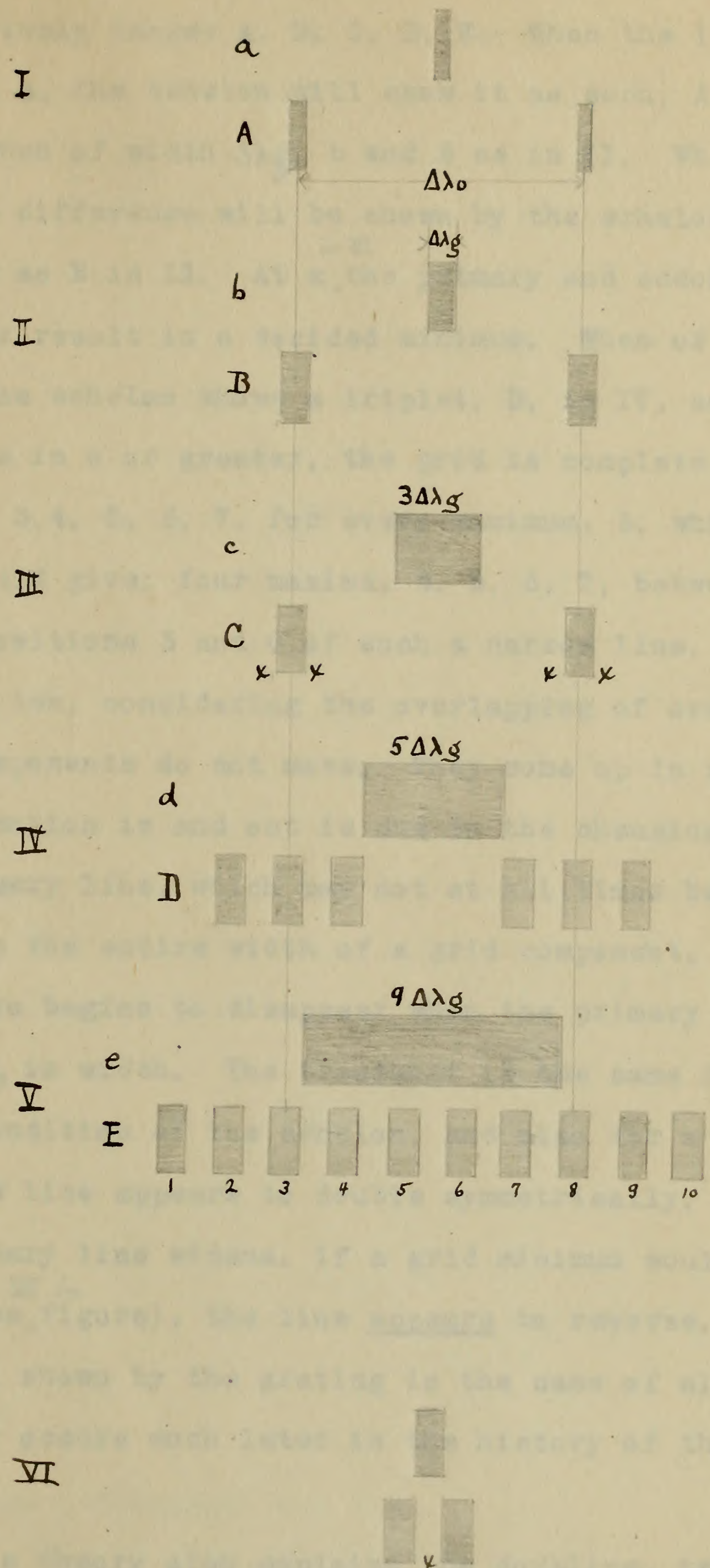


grid in the echelon.(See sketch). Its width in the grating at this pole was measured roughly with a millimeter scale. When compared with the distance between two lines of known wave-length, the width proved to be about 0.25 Å. The separation of the orders in the echelon for this wave-length is about 0.26 Å. Consequently under these conditions the line is too broad for successful study with this instrument, and thus we have further proof that the grid cannot be structure which is real in the source.

It is evident that when the line is in the condition to show the grid, it constitutes a little chunk of continuous spectrum 0.25 Å, or greater, in width. As stated above, Stansfield leaves the reader to draw his own conclusions as to why secondary maxima should be formed easily in such a case. The secondary light, having passed through

more glass than the primary and being produced by feeble reflections at best, must be much weaker than the primary, and its effect must be masked if the latter is sufficiently intense. Furthermore the secondary maxima, which from the theory of their origin are the same as a Fabry and Perot system, must be all of the same wave-length, and yet it will be remembered that crossing a Lummer plate with the echelon showed the grid lines to be of different wave-lengths. May it not be that the secondary maxima make themselves visible by a reinforcement of the continuous spectrum at the points where they would ordinarily occur, in a manner not unlike the production of beats in the case of sound waves? The secondary light having about five times the retardation should come into phase with the primary light about five times while passing from one primary order to the next. At intermediate points the two should be out of phase and tend to annul each other. Maxima produced in this way would be of different wave-lengths, and thus the point system given by crossed Lummer plate and echelon would be explained. Furthermore, when the doublet components are single as in the vacuum tube at low pressure, but beginning to broaden, as soon as they reach a width equal to $\Delta\lambda g$, the secondary action will cause them to twin, the components coming up in their final places and not moving out from the line as in ordinary reversal. It is quite certain that the grid is built up in the following manner: suppose that in a hypothetical grating of resolving power, and dispersion equal to that of the echelon, a line which is at first very narrow, e.g., 0.025 Å, gradually becomes less monochromatic, owing to changing conditions in the

more glass than the primary and being produced by feeble reflections at best, must be much weaker than the primary, and its effect must be masked if the latter is sufficiently intense. Furthermore the secondary maxima, which from the theory of their origin are the same as a Fabry and Perot system, must be all of the same wave-length, and yet it will be remembered that crossing a Lummer plate with the echelon showed the grid lines to be of different wave-lengths. May it not be that the secondary maxima make themselves visible by a reinforcement of the continuous spectrum at the points where they would ordinarily occur, in a manner not unlike the production of beats in the case of sound waves? The secondary light having about five times the retardation should come into phase with the primary light about five times while passing from one primary order to the next. At intermediate points the two should be out of phase and tend to annul each other. Maxima produced in this way would be of different wave-lengths, and thus the point system given by crossed Lummer plate and echelon would be explained. Furthermore, when the doublet components are single as in the vacuum tube at low pressure, but begining to broaden, as soon as they reach a width equal to $\Delta\lambda_E$, the secondary action will cause them to twin, the components coming up in their final places and not moving out from the line as in ordinary reversal. It is quite certain that the grid is built up in the following manner: suppose that in a hypothetical grating of resolving power, and dispersion equal to that of the echelon, a line which is at first very narrow, e.g., 0.025 A. gradually becomes less monochromatic, owing to changing conditions in the


a
I
A
$\Delta\lambda_o$
$\Delta\lambda g$
b
II
B
$3\Delta\lambda g$
c
III
C
x x x x
$5\Delta\lambda g$
d
IV
D
$9\Delta\lambda g$
e
V
E
1 2 3 4 5 6 7 8 9 10
VI
x

source, and appears as in a, b, c, d, e in the figure. The echelon in double order condition will then actually show successively images A, B, C, D, E. When the line is very narrow, a, the echelon will show it as such, A, in I. Similarly when of width $\Delta\lambda_g$, b and B as in II. When of width $3\Delta\lambda_g$ no difference will be shown by the echelon: C in III appears as B in II. At x in III the primary and secondary action together result in a decided minimum. When of width, as in d, the echelon shows a triplet, D, in IV, and when of width as in e or greater, the grid is complete, five grid maxima, 3, 4, 5, 6, 7, for every maximum, 3, which a narrow line would give; four maxima, 4, 5, 6, 7, between the double order positions 3 and 8 of such a narrow line, and a total of even ten, considering the overlapping of orders. These grid components do not move. They come up in situ. Apparent motion in and out is due to the changing of width of the primary line, which may not at all times be such as to complete the entire width of a grid component. The grid structure begins to disappear when the primary line exceeds 2 (?)$\Delta\lambda_g$ in width. The treatment is the same for a single-order-condition of the echelon, and also for a case in which a narrow line appears to double symmetrically. Thus, as the primary line widens, if a grid minimum would occur at x (see in VI figure), the line <u>appears</u> to reverse. (True reversal shown by the grating in the case of all lines, probably occurs much later in the history of the line)

This theory also explains the doubling, tripling, and quadrupling of the zinc lines, and shows why only certain lines exhibit this structure, namely, those which broaden

source, and appears as in a, b, c, d, e in the figure. The echelon in double order condition will then actually show successively images A, B, C, D, E. When the line is very narrow, a, the echelon will show it as such, A, in I. Similarly when of width $\Delta\lambda_s$, b and B as in II. When of width $3\Delta\lambda_s$ no difference will be shown by the echelon: C in III appears as B in II. At x, the primary and secondary action together result in a decided minimum. When of width, as in d, the echelon shows a triplet, D, in IV, and when of width as in e or greater, the grid is complete, five grid maxima, 3, 4, 5, 6, 7, for every maximum, 5, which a narrow line would give; four maxima, 4, 5, 6, 7, between the double order positions 5 and 8 of such a narrow line, and a total of even ten, considering the overlapping of orders. These grid components do not move. They come up in situ. Apparent motion in and out is due to the changing of width of the primary line, which may not at all times be such as to complete the entire width of a grid component. The grid structure begins to disappear when the primary line exceeds 2 (?)$\Delta\lambda_s$ in width. The treatment is the same for a single-order-condition of the echelon, and also for a case in which a narrow line appears to double symmetrically. Thus, as the primary line widens, if a grid minimum would occur at x (see figure), the line appears to reverse. (True reversal shown by the grating in the case of all lines probably occurs much later in the history of the line)

This theory also explains the doubling, tripling, and quadrupling of the zinc lines, and shows why only certain lines exhibit this structure, namely, those which broaden

considerably with increase of vapor in the source.

Since the secondary action sets in when a line attains a width equal to $\Delta\lambda_g$, and produces two lines, it follows that a line of such breadth is unsuited for study with the echelon. Users of this instrument will have noticed that the lines which they have seen to best advantage have all been narrow and usually sharp. For example each of the magnificent array of satellites given by the green line of mercury, λ 5461, always appears clear and fine. The writer has further noticed that with the Petitdidier instrument the main component of this line usually has a tendency toward apparent reversal even in a Cooper-Hewitt lamp viewed side on. Since in this instrument the main line has a width greater than $\Delta\lambda_g$, is it not likely that this tendency is due to the secondary action? If so, we are then forced to the conclusion that the echelon instead of being suitable for studying lines of any width not greater than the distance between the orders, is reliable only for lines which are themselves as well as their satellites narrower than about one-fifth the separation of the orders.

Conclusions.

(1) The stronger component of the spectroscopic doublet, Li λ 6104, when observed under high resolving power, appears to have a faint satellite.

(2) The grid structure is due to secondary maxima given by the echelon.

(3) Only such lines as broaden considerably with increase in intensity can show the grid structure.

(4) The brilliancy and clearness of this structure are due to the reinforcing action of the secondary light ~~maxima~~ upon the short continuous spectrum composing the broad line over a distance of the order equal to $\Delta\lambda_0$.

(5) The echelon grating is reliable for the study of line structure only when the line investigated is less in width than one-fifth of the separation of the orders.

The writer wishes to express his deep appreciation of Prof. Norton A. Kent's enthusiastic cooperation throughout the whole of this work. The success of the investigation has depended very largely on his invaluable assistance.

Bibliography.

(1) Humphreys and Mohler, Astrophysical Journal VI 169 (1897)

(2) Exner and Haschek, Astrophysical Journal XIV 181 (1901)

(3) Kent, Astrophysical Journal XXII 182 (1905)

(4) St. John and Babcock, Astrophysical Journal XLII 1 (1915)

(5) Nutting, Astrophysical Journal XXIII 64 (1906)

(6) Janicki, Annalen der Physik — Band 29 (1909)

(7) Kent, Proceedings of the American Academy of Arts and Sciences XLVIII 91 (1912)

(8) Kent, Astrophysical Journal XL 337 (1914)

(9) King, Astrophysical Journal XLIV 397 (1916)

(10) Baly, Spectroscopy, Ed. 1912, page 193.

(11) Stansfield, Philosophical Magazine (6) 18, 383 (1909)